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THE INFLUENCE OF EXHAUST PRESSURE ON
KNOCK-LIMITED PERFORMANCE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Forces, Air Technical Service Command

THE INFLUENCE OF EXHAUST PRESSURE ON KNOCK-LIMITED PERFORMANCE

By Harvey A. Cook, Louis F. Held, and Ernest I. Pritchard

SUMMARY

Tests were conducted on two types of single cylinder to determine the effect of the relation of exhaust pressure to inlet-air pressure on knock-limited performance. The variables studied with one cylinder were exhaust pressure, fuel-air ratio, and engine speed. Exhaust pressure only was studied with the other.

The effect of exhaust pressure on fuel ratings was investigated in cylinder tests of three aircraft-engine fuels (28-R, 97-percent 28-R with 3-percent xylidines leaded to 6 ml TEL/gal, and 80-percent 28-R with 20-percent triptane leaded to 4.6 ml TEL/gal) in tests with varied spark advance at a fuel-air ratio of 0.065.

The test results indicate that knock-limited performance was very sensitive to exhaust pressure when the inlet-air pressure was approximately equal to the exhaust pressure.

In tests at a fuel-air ratio of 0.065 in which the exhaust pressure was varied from 5 to 40 inches of mercury absolute, the knock-limited indicated mean effective pressure was lowered 55 percent. The knock-limited inlet-air pressure was equal to the exhaust pressure at 23.5 inches of mercury absolute, and more than half of the 55-percent reduction in indicated mean effective pressure occurred when the exhaust pressure varied from 20 to 25 inches of mercury absolute.

INTRODUCTION

At the request of the Army Air Forces, Air Technical Service Command, an investigation is being conducted at the Cleveland laboratory of the NACA to evaluate high-antiknock compounds of aviation fuels. When check tests were being run during this investigation, a variation in knock-limited inlet-air pressure from 8 to 10 inches of mercury occasionally appeared around a fuel-air ratio of 0.065. This variation of the lean-mixture knock limit was observed to occur at engine conditions of such a degree of severity that the knock-limited inlet-air pressure was approximately equal to the exhaust pressure. This observation led to the study of the effect of exhaust pressure on knock-limited performance and the findings are presented in this report. The effect of exhaust pressure on detonation was studied at the Massachusetts Institute of Technology in an investigation reported in reference 1.

Single-cylinder tests were conducted during the fall of 1944 with two aircraft-engine cylinders to determine the effect of the relation of exhaust pressure to inlet-air pressure on knock-limited performance and on fuel ratings and the results are presented in this paper.

APPARATUS AND TEST PROCEDURE

A R-2600 front-row cylinder (cylinder A) and an R-1830 front-row cylinder (cylinder B) were tested in similar setups, arranged as shown in figure 1. The cylinders were fitted with standard baffles and, because some turbulence was induced in the air stream ahead of the cylinder, the cooling was considered to simulate the cooling of an engine in flight.

Cylinder-head temperature was measured by an iron-constantan thermocouple in the head 1/4 inch below the rear spark plug. This cylinder-head temperature was maintained constant in all cylinder A tests by adjusting the cooling-air flow. Tests with cylinder B were run at a constant cooling-air pressure drop (16.5 in. water), and the cylinder-head temperature varied from 391° to 420° F.

A fuel-vaporization tank, diagrammatically shown in figure 2, was used for all tests with cylinder B. In tests with cylinder A, fuel was injected during the intake stroke into the intake manifold approximately 14 inches from the intake valve except in the tests with varied spark advance when a vaporization tank similar to the one in the cylinder B setup was used.

Exhaust pressure was measured by a mercury manometer connected to the exhaust muffler and was controlled by valves in the line to the altitude-exhaust system. A magnetostriction-type pickup and a cathode-ray oscillograph were used to detect incipient knock.

The following engine conditions were maintained constant, except where noted, during the tests:

	Cylinder A (R-2600)		Cylinder B (R-1830)	
Engine speed, rpm.....	2100	2500	2100	2230
Inlet-air temperature, °F (before fuel injection).....	250	250	250	260
Cylinder-head temperature, °F.....	450	450	450	varied
Spark advance, degrees B.T.C. (both plugs).....	20	20	varied	25
Compression ratio.....	6.9	6.9	6.9	6.7
Cooling-air temperature, °F.....	90	90	90	85
Valve timing, crank angle:				
Intake valve opens, degrees B.T.C.....	20	20	20	20
Intake valve closes, degrees B.T.C.....	130	130	130	104
Exhaust valve opens, degrees A.T.C.....	115	115	115	104
Exhaust valve closes, degrees A.T.C.....	40	40	40	20

In all cylinder A tests at a spark advance of 20° B.T.C., 28-R fuel was used. The following fuels, for which F-3 and F-4 ratings were obtained at the NACA Cleveland laboratory, were compared in cylinder A in tests with varied spark advance:

Fuel	F-3 rating (octane number)	F-4 rating (Army-Navy performance number)
28-R	99.8	132
97-percent 28-R with 3-percent xylidines leaded to 6 ml TEL per gallon	99.5	151
80-percent 28-R with 20-percent triptane leaded to 4.6 ml TEL per gallon	^a 109	147

^aArmy-Navy performance number.

The fuel used in all tests with cylinder B was AN-F-26, Amendment-2 (grade 91/96).

RESULTS AND DISCUSSION

Effect of Exhaust Pressure on Knock-Limited Performance

Tests of cylinder A at constant fuel-air ratios. - The effect of exhaust pressure p_e was studied with cylinder B in a series of tests at constant fuel-air ratio at 2100 rpm. The procedure was to vary the exhaust pressure and to operate at incipient knock by adjusting the inlet-air pressure p_i . The effects of exhaust pressure on knock-limited performance for fuel-air ratios from 0.055 to 0.10 are presented in figure 3. Because of the difficulty in running knock tests at constant fuel-air ratios, some data were obtained at fuel-air ratios that deviated more than 0.001 from the desired constant value. The fuel-air ratios that deviated from the desired constant values are noted on the data points for the curves of indicated mean effective pressure. Check tests (indicated by tailed symbols) run at a fuel-air ratio of 0.065 with decreasing and increasing exhaust pressure showed that the results were unaffected by the method of running the tests.

That the knock-limited performance was lowered by increasing the exhaust pressure is illustrated in figure 3. Little change in knock limit was noted until the exhaust pressure was about 10 inches of mercury below the inlet-air pressure. At this point the knock-limited inlet-air pressure and the indicated mean effective pressure began to decrease rapidly, continuing until the exhaust pressure was approximately 5 inches of mercury above the inlet-air pressure; the rate of change in knock limit was greatest when the exhaust pressure and the inlet-air pressure were approximately equal. The region of rapid decrease in knock limit, as defined by the difference between the inlet-air and the exhaust pressure, will hereinafter be referred to as the "critical" $p_i - p_e$ range. For the data presented in figure 3, the limits of the critical $p_i - p_e$ range were 10 to -5 inches of mercury. These two values as well as $p_i - p_e$ value of 0 are shown in the figure by dashed lines.

Because the decrease in knock-limited performance in the critical $p_i - p_e$ range was greater at fuel-air ratios of approximately 0.065 than at other mixture strengths and because exhaust gases are hottest at a fuel-air ratio of about 0.065 (discussed in reference 2), the effects on performance in the critical $p_i - p_e$ range can be attributed to heating of the charge by the residual gases.

The amount of residual gases and, consequently, the resultant effect on engine performance depends primarily on cylinder scavenging. The effect of the difference between inlet-air and exhaust pressures, particularly during the critical $p_i - p_e$ range, on cylinder scavenging is illustrated in figure 4, in which combustion-air flow is plotted against $p_i - p_e$ for the data presented in figure 3.

In order to show the effect of the critical $p_i - p_e$ range on knock-limited performance, the data in figure 3 were cross-plotted at several constant exhaust pressures in figure 5. The relative shapes of the curves show the effect of critical $p_i - p_e$ range and again indicate that the effect is greatest at fuel-air ratios around 0.065.

Tests of cylinder A at 2500 rpm. - Knock tests at 2500 rpm were made to determine whether the critical $p_i - p_e$ range would be different at another engine speed. The results of a test at a constant fuel-air ratio (0.065) with varied exhaust pressure, presented in figure 6, indicate that a similar critical $p_i - p_e$ range occurred at this higher engine speed.

Tests of cylinder B. - In order to determine whether the critical $p_i - p_e$ range was peculiar to cylinder A, tests were conducted with a cylinder of different displacement and with different valve timing. Essentially the same type of variation in knock-limited performance with exhaust pressure is to be observed with this cylinder as with cylinder A. (See fig. 7.)

Check tests of cylinder A. - When the check tests were begun, the original cylinder A used in the investigation was replaced by a similar cylinder, hereinafter referred to as "check-test" cylinder A. Analysis of the data in figure 3 showed that check tests could be run to advantage at constant values of $p_i - p_e$ by adjusting the exhaust pressure and that a comparison with previous tests could be made by cross-plotting the data. This procedure obviated the difficulty of running knock tests at constant fuel-air ratios. Two tests at constant fuel-air ratios (0.065 and 0.085) were made to check the cross-plotted data. The check-test data and the cross plots for checking the test results presented in figures 3 and 5 are presented in figures 8, 9, and 10. For comparison, the data showing knock-limited indicated mean effective pressure of figures 5 and 10 are replotted in figure 11.

The same critical $p_i - p_e$ range was found in the check tests as in the original tests, although the knock-limited performance was higher. The reason for the higher knock-limited performance is not

known, but the check tests were considered to be adequate because they showed effects of exhaust pressure similar to those observed in tests with the original cylinder.

The effect of the critical $p_i - p_e$ range is shown by the distortion of the mixture-response curves (figs. 5 and 10) run at exhaust pressures when the critical range was encountered in contrast to the curves at other exhaust pressures. The distortion results from the increase in slope of the curve in the critical range. Comparison of the two cylinders at a fuel-air ratio of 0.065 (fig. 11) shows a variation from 18 to 72 percent in the increase of knock-limited indicated mean effective pressure. This variation resulted because the critical $p_i - p_e$ range (figs. 3 and 9) occurred at different exhaust pressures for the two cylinders.

The greater variation shown for lean mixtures relative to rich mixtures is evidence that operation in the critical $p_i - p_e$ range can account for the greater variation of lean-mixture knock-limited performance than rich-mixture knock-limited performance.

Effect of Exhaust Pressure on Fuel Ratings

In order to investigate to what extent a comparison of fuels can be affected by the critical $p_i - p_e$ range, knock tests of three high-performance fuels were conducted at atmospheric exhaust pressure (sea level) and at an exhaust pressure of 15 inches of mercury absolute (atmospheric pressure at approximately 18,000 ft). Cylinder A was used in tests at variable spark advance at a fuel-air ratio of 0.065. The test results, presented in figure 12, show that the critical $p_i - p_e$ range was reached in the tests at atmospheric exhaust pressure (sea level) but not at 15 inches of mercury absolute. In the critical $p_i - p_e$ range, the steepest drop in knock limit again occurred when p_i was equal to p_e .

A comparison of the high-performance fuels with 28-R at two exhaust pressures and several spark advances is shown in the following table:

Fuel	Exhaust pressure, p_e	Percentage increase in knock-limited imep of high-performance fuels relative to 28-R				
		Spark advance, degrees B.T.C.				
		20	25	30	35	40
97-percent 28-R with 3-percent xyli- dines leaded to 6 ml TEL/gal	Atmospheric (sea level)	0.0	0.0	0.0	0.0	0.0
	15 in. Hg abs. ^a	4.3	6.4	9.0	7.9	7.9
80-percent 28-R with 20-percent tri- pane leaded to 4.6 ml TEL/gal	Atmospheric (sea level)	5.7	0.0	0.0	0.0	0.0
	15 in. Hg abs. ^a	9.2	12.1	15.5	17.3	18.9

^aAtmospheric pressure at approximately 13,000 ft.

The shapes of the curves in figure 12 and the foregoing comparisons show very clearly that exhaust pressure can have a very marked effect on knock-limited performance and fuel ratings.

CONCLUDING REMARKS

The effects of exhaust pressure on knock-limited performance were determined in a series of tests with two air-cooled, full-scale, single-cylinder engines. Knock-limited performance was very sensitive to exhaust pressure when the inlet-air pressure was approximately equal to the exhaust pressure.

When the exhaust pressure was increased in tests at constant fuel-air ratios, little change in knock limit was noted until the exhaust pressure was about 10 inches of mercury below the inlet-air pressure. At this point the knock limit began to decrease rapidly, continuing until the exhaust pressure was approximately 5 inches of mercury above the inlet-air pressure; the rate of change in the knock limit was greatest when the exhaust pressure and the inlet-air pressure were approximately equal.

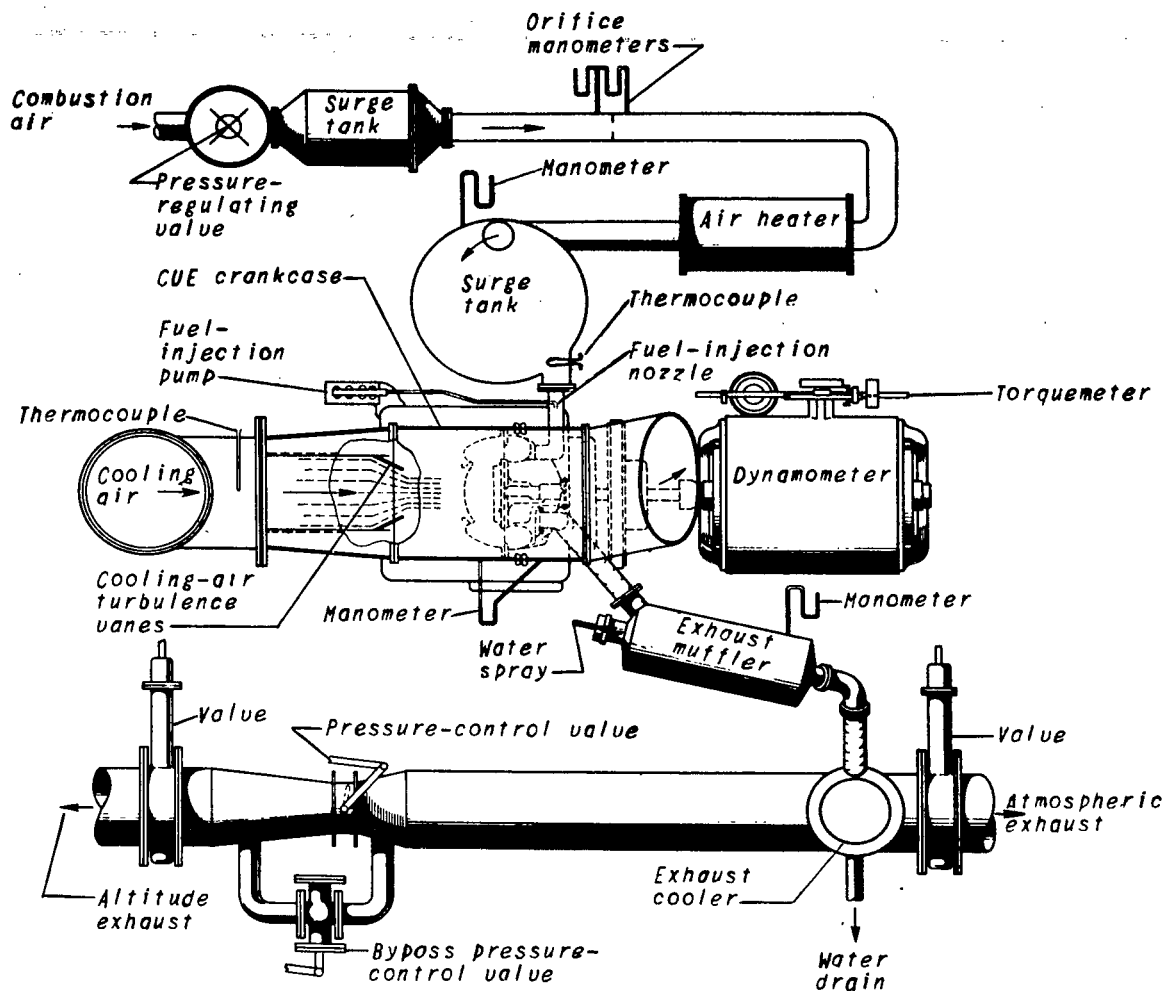
Mixture-response curves are distorted by the effect of the relation of inlet-air pressure and exhaust pressure in the region described in the preceding paragraph. Comparisons of knock-limited

performance of fuels can be greatly affected by the changes in the shapes of the mixture-response curves, caused by the effects of exhaust pressure.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, January 5, 1945.

REFERENCES

1. Taylor, E. S., Leary, W. A., and Diver, J. R.: Effect of Fuel-Air Ratio, Inlet Temperature, and Exhaust Pressure on Detonation. NACA Rep. No. 699, 1940.
2. Cook, Harvey A., Vandeman, Jack E., and Brown, Kenneth D.: Effect of Several Methods of Increasing Knock-Limited Power on Cylinder Temperatures. NACA ARR No. E4115, 1944.



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Figure 1. - Arrangement of apparatus for single-cylinder set-ups.

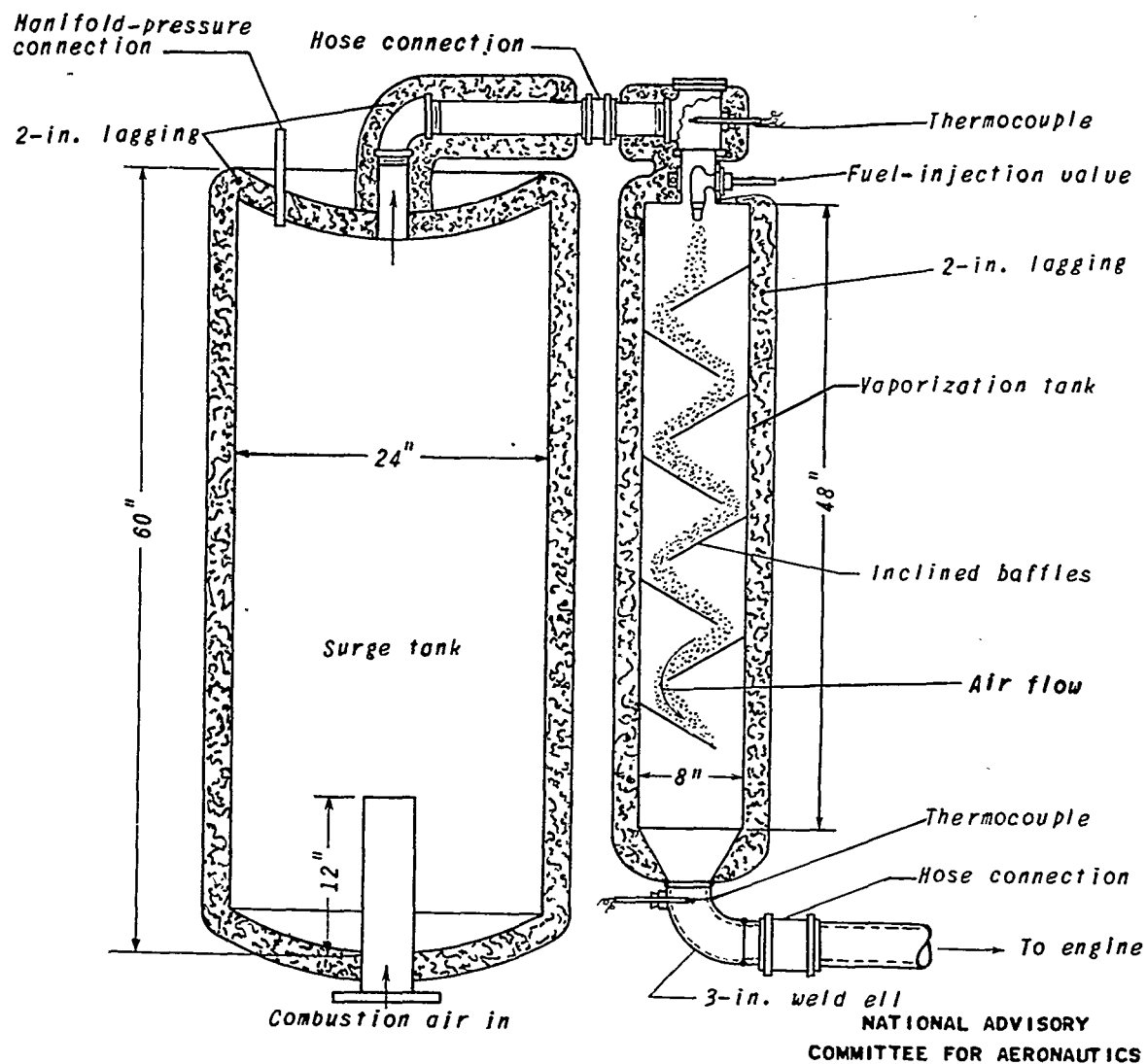


Figure 2. - Surge tank and fuel-vaporization tank for test setup for cylinder B.

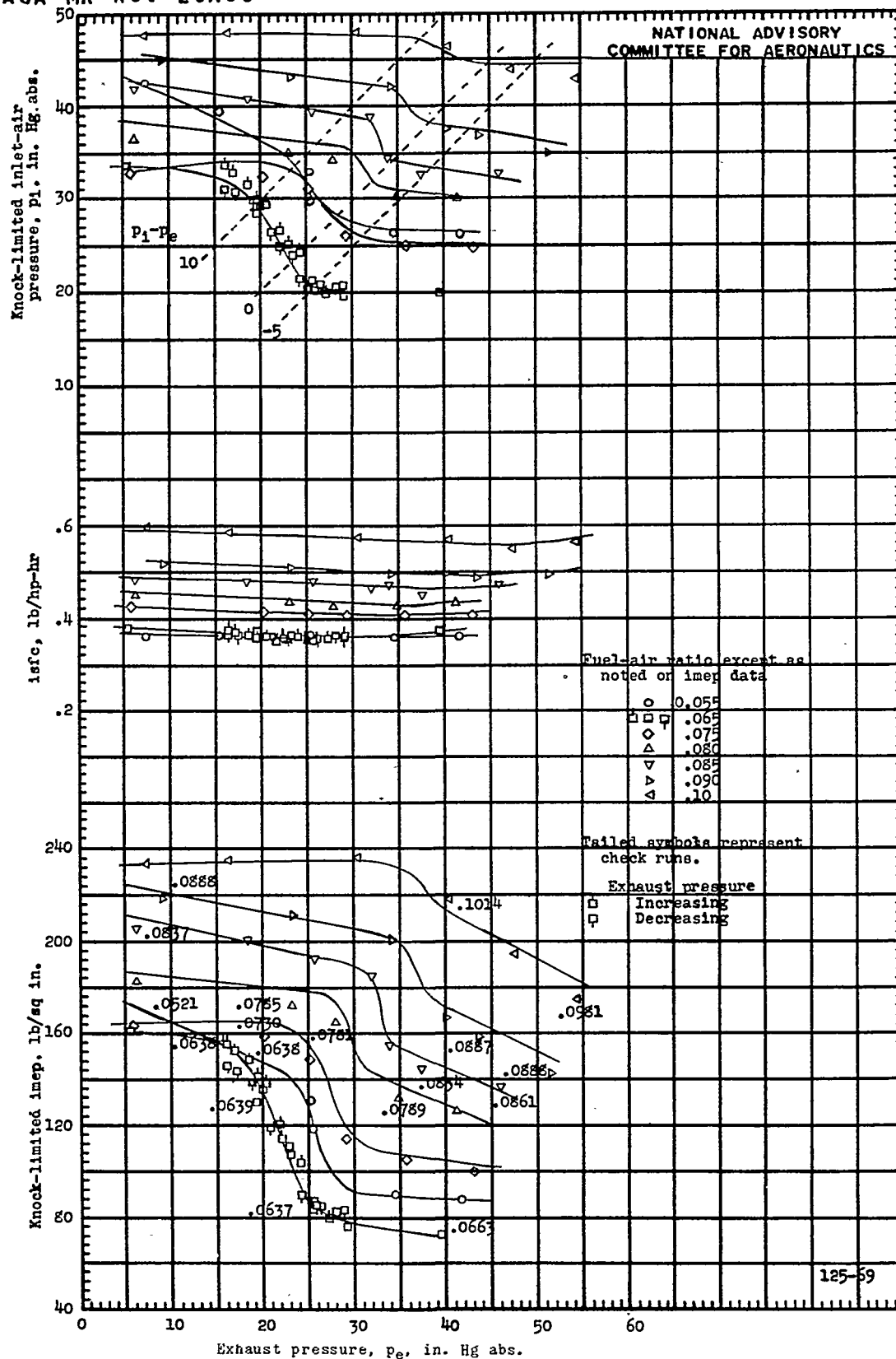


Figure 3. - Effect of exhaust pressure on knock-limited performance of cylinder A in tests at constant fuel-air ratios. Engine speed, 2100 rpm; inlet-air temperature, 250° F; spark advance, 20° B.T.C.; cylinder-head temperature, 450° F; compression ratio, 6.9; fuel, 28-R.

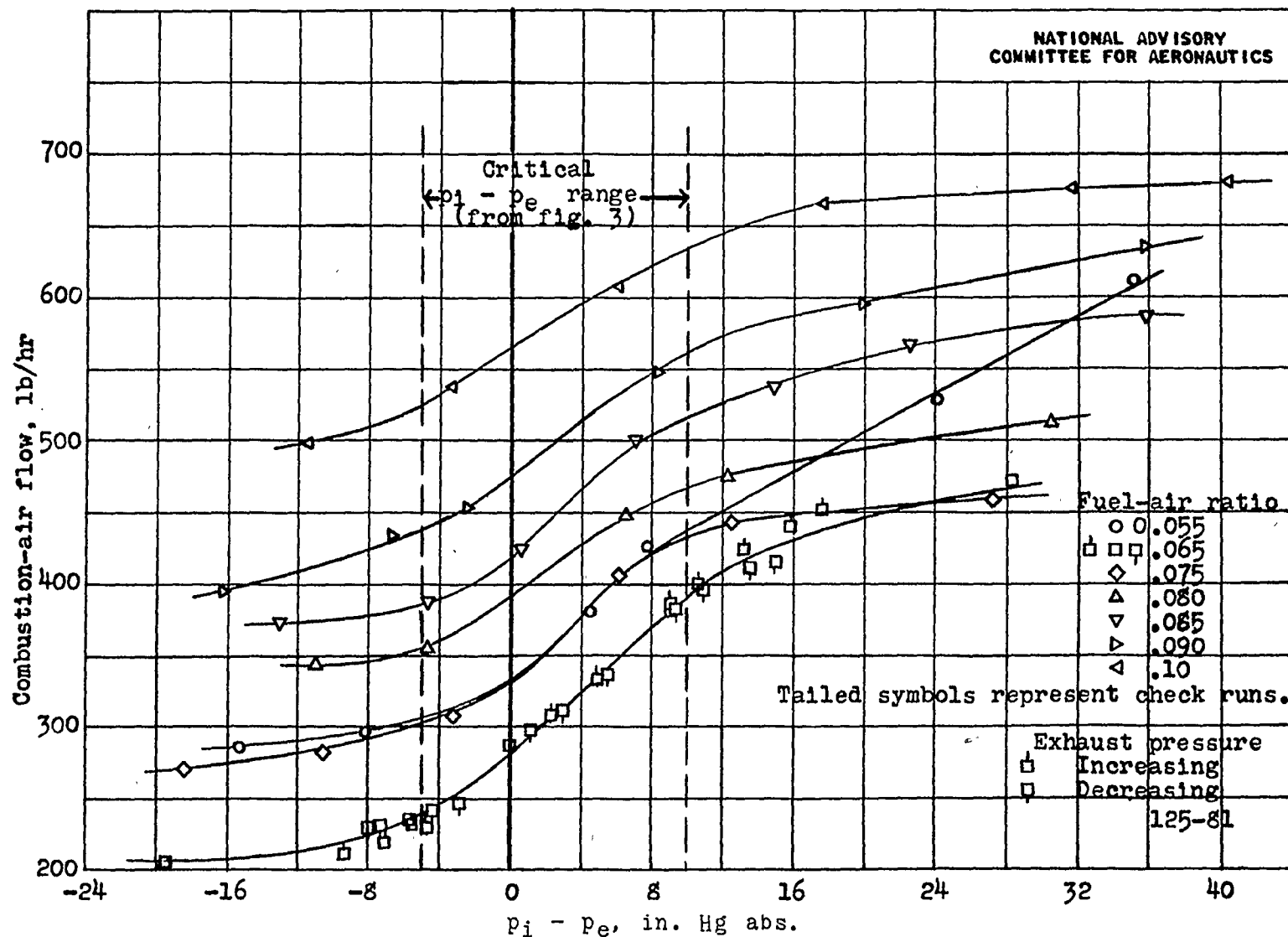


Figure 4. - Effect of difference between inlet-air pressure p_i and exhaust pressure p_e on combustion-air flow of cylinder A in tests at constant fuel-air ratios.

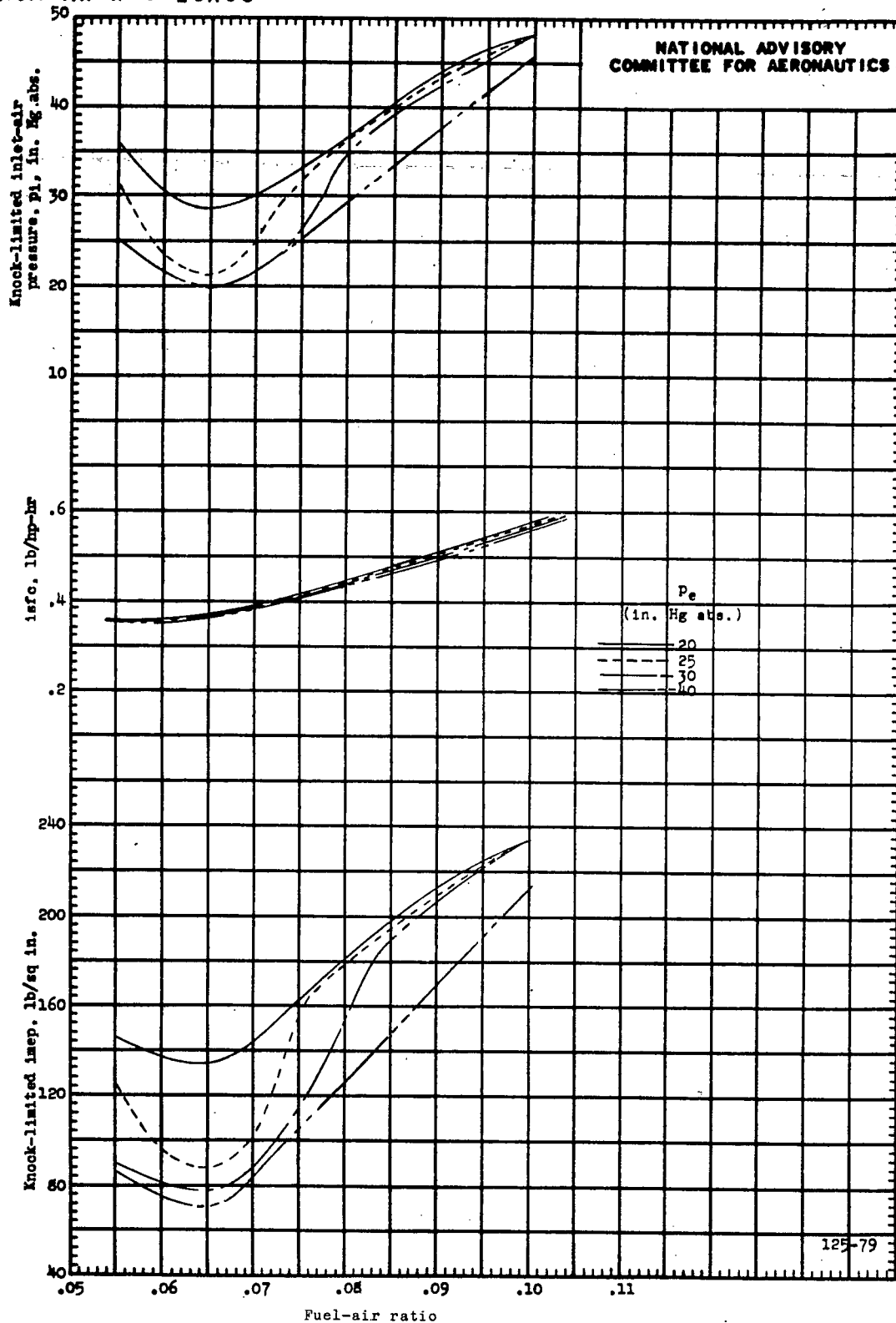


Figure 5. - Effect of exhaust pressure p_e and critical $p_i - p_e$ range on knock-limited performance of cylinder A at constant exhaust pressures. (Cross plot from fig. 3.) Engine speed, 2100 rpm; inlet-air temperature, 250° F; spark advance, 20° B.T.C.; cylinder-head temperature, 450° F; compression ratio, 6.9; fuel, 28-R.

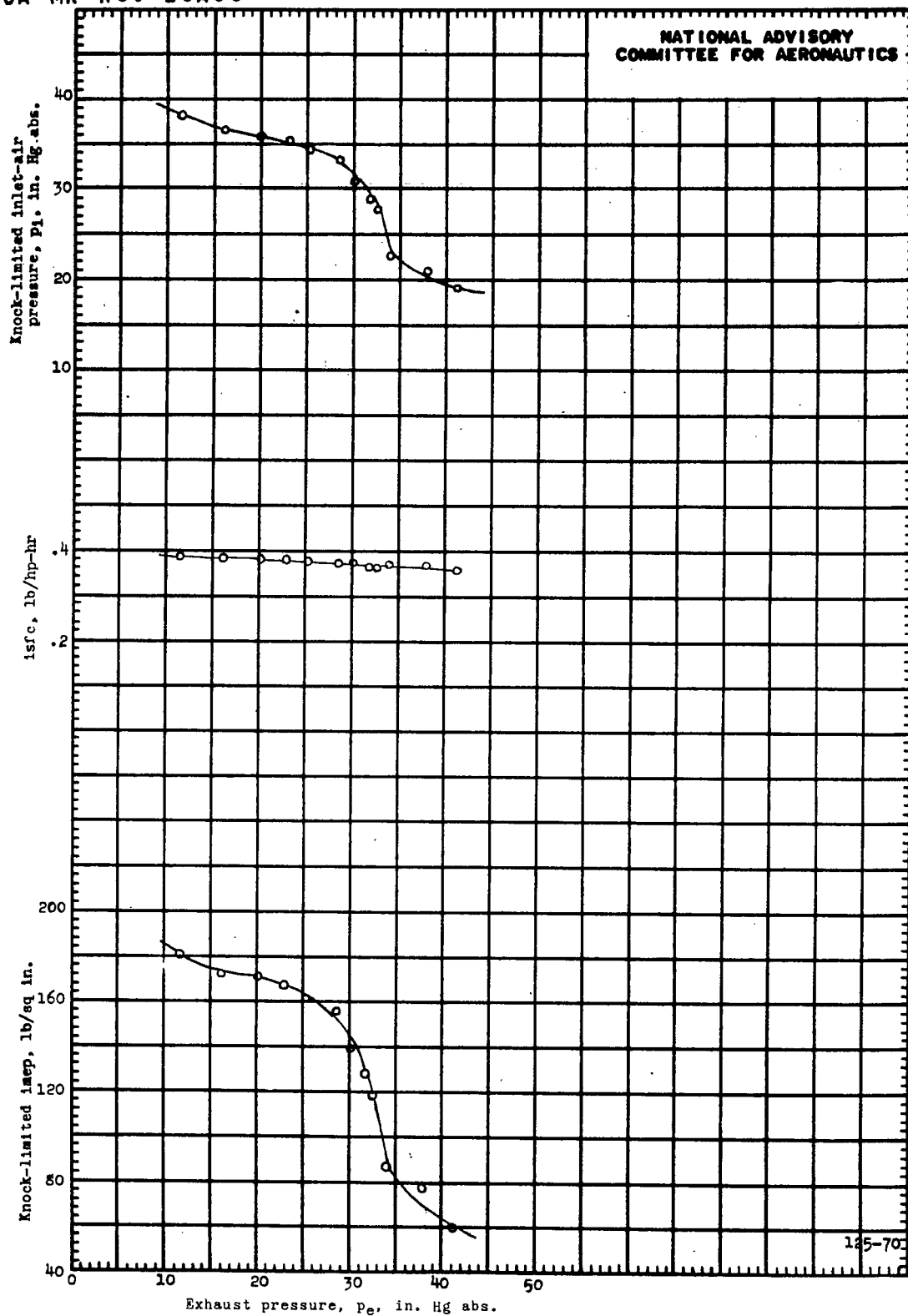


Figure 6. - Effect of exhaust pressure on knock-limited performance of cylinder A at an engine speed of 2500 rpm. Fuel-air ratio, 0.065; inlet-air temperature, 250° F; spark advance, 20° B.T.C.; cylinder-head temperature, 450° F; compression ratio, 6.9; fuel, 28-R.

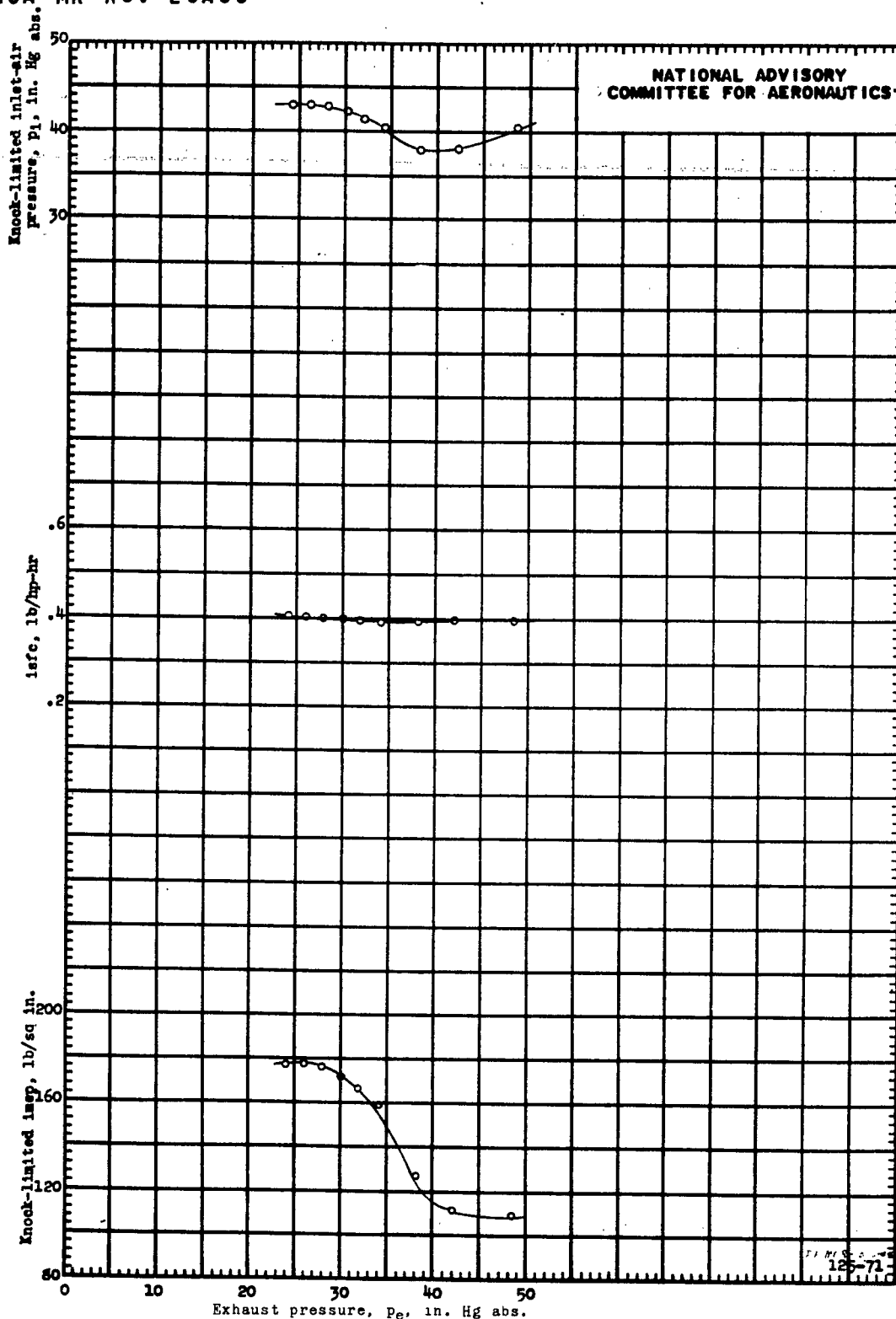


Figure 7. - Effect of exhaust pressure on knock-limited performance of cylinder B. Engine speed, 2230 rpm; fuel-air ratio, 0.065; inlet-air temperature, 260° F; spark advance, 25° B.T.C.; cooling-air pressure drop, 16.5 inches of water; compression ratio, 6.7; fuel, AN-F-28, Amendment-2.

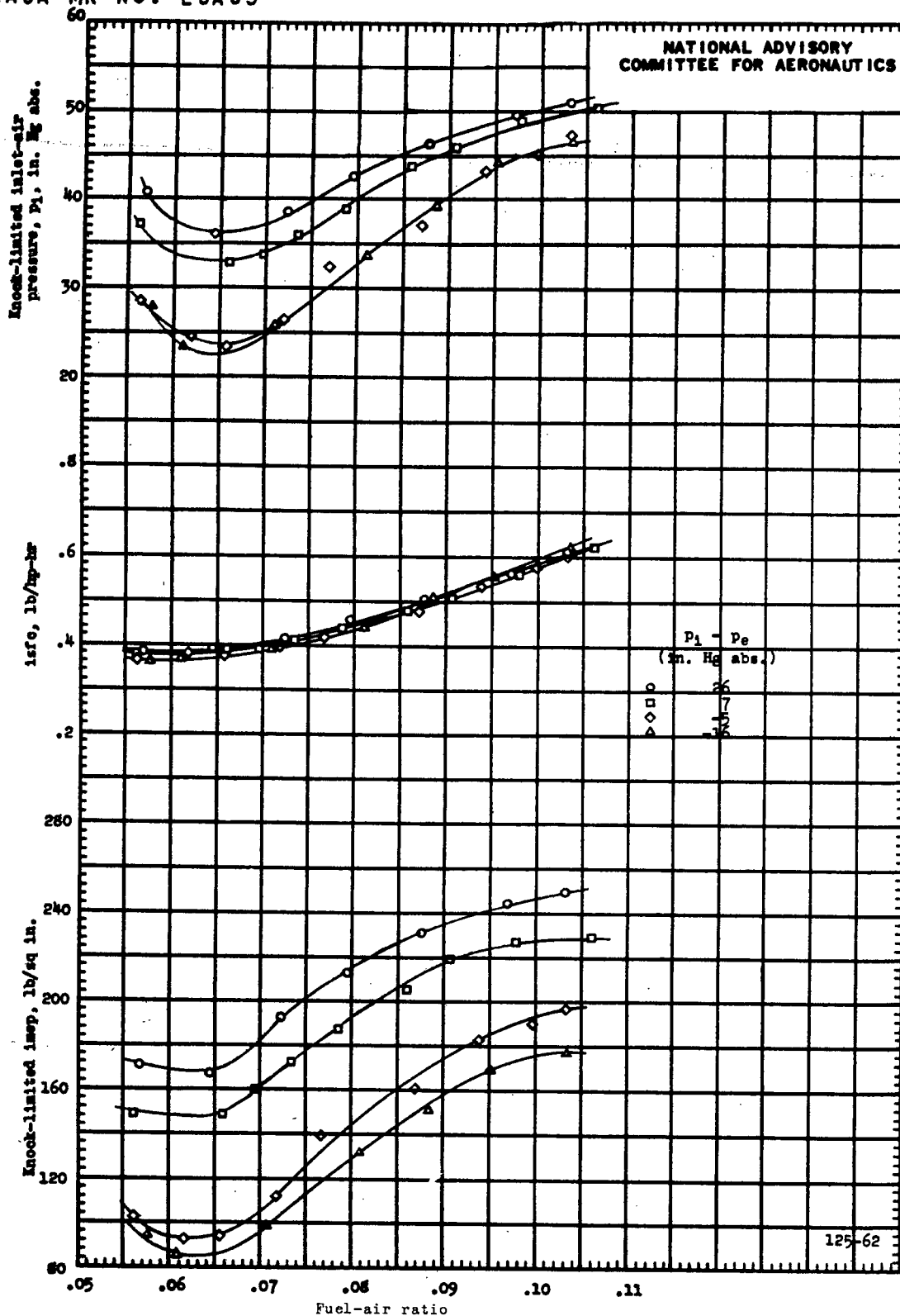


Figure 8. - Knock-limited performance of the check-test cylinder A at constant values of $P_1 - P_0$. Engine speed, 2100 rpm; inlet-air temperature, 250° F; spark advance, 20° B.T.C.; cylinder-head temperature, 450° F; compression ratio, 6.9; fuel, 28-R.

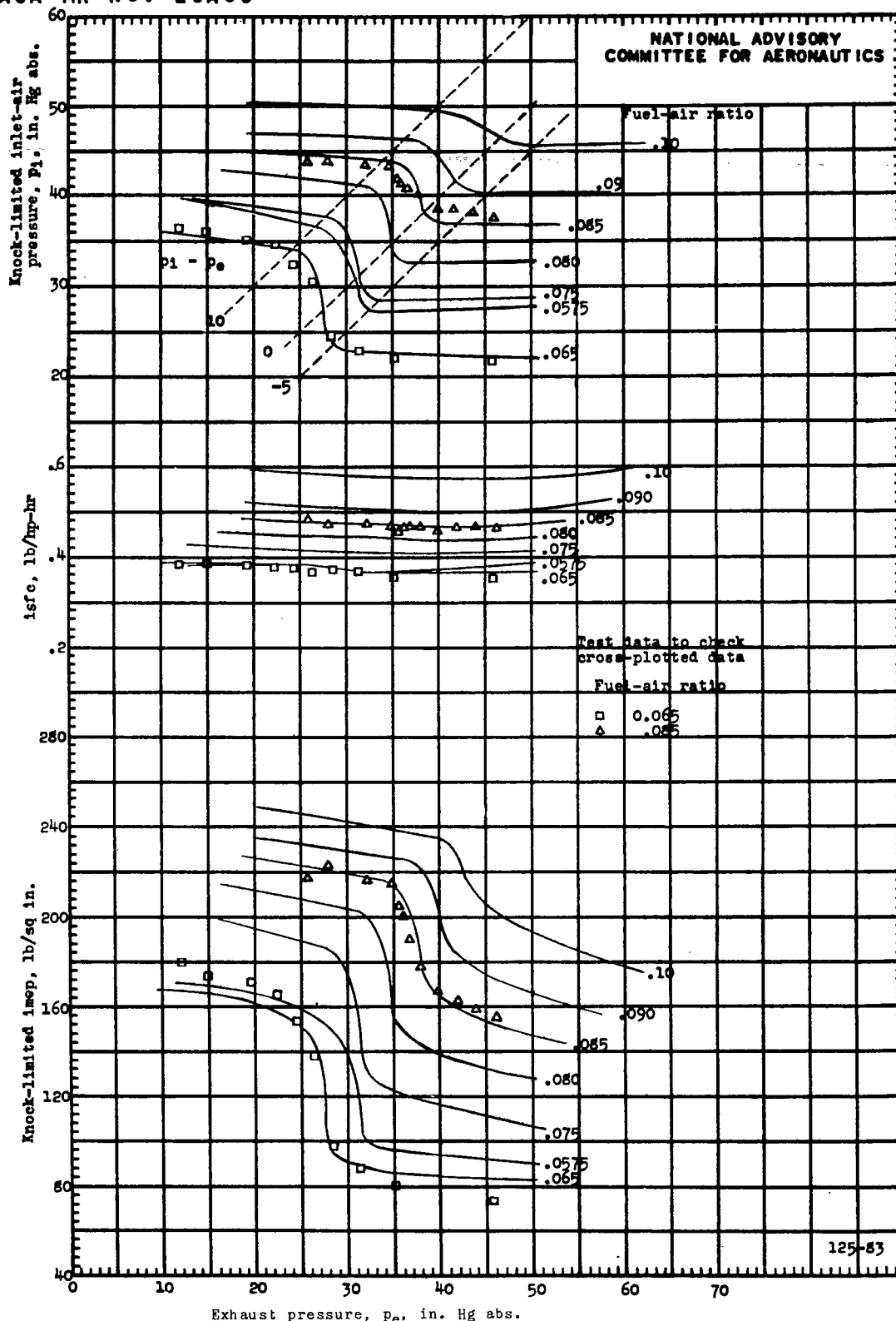


Figure 9. - Effect of exhaust pressure on knock-limited performance of the check-test cylinder A in tests at constant fuel-air ratios. (Cross plot from fig. 8.) Engine speed, 2100 rpm; inlet-air temperature, 250° F; spark advance, 20° B.T.C.; cylinder-head temperature, 450° F; compression ratio, 6.9; fuel, 28-R.

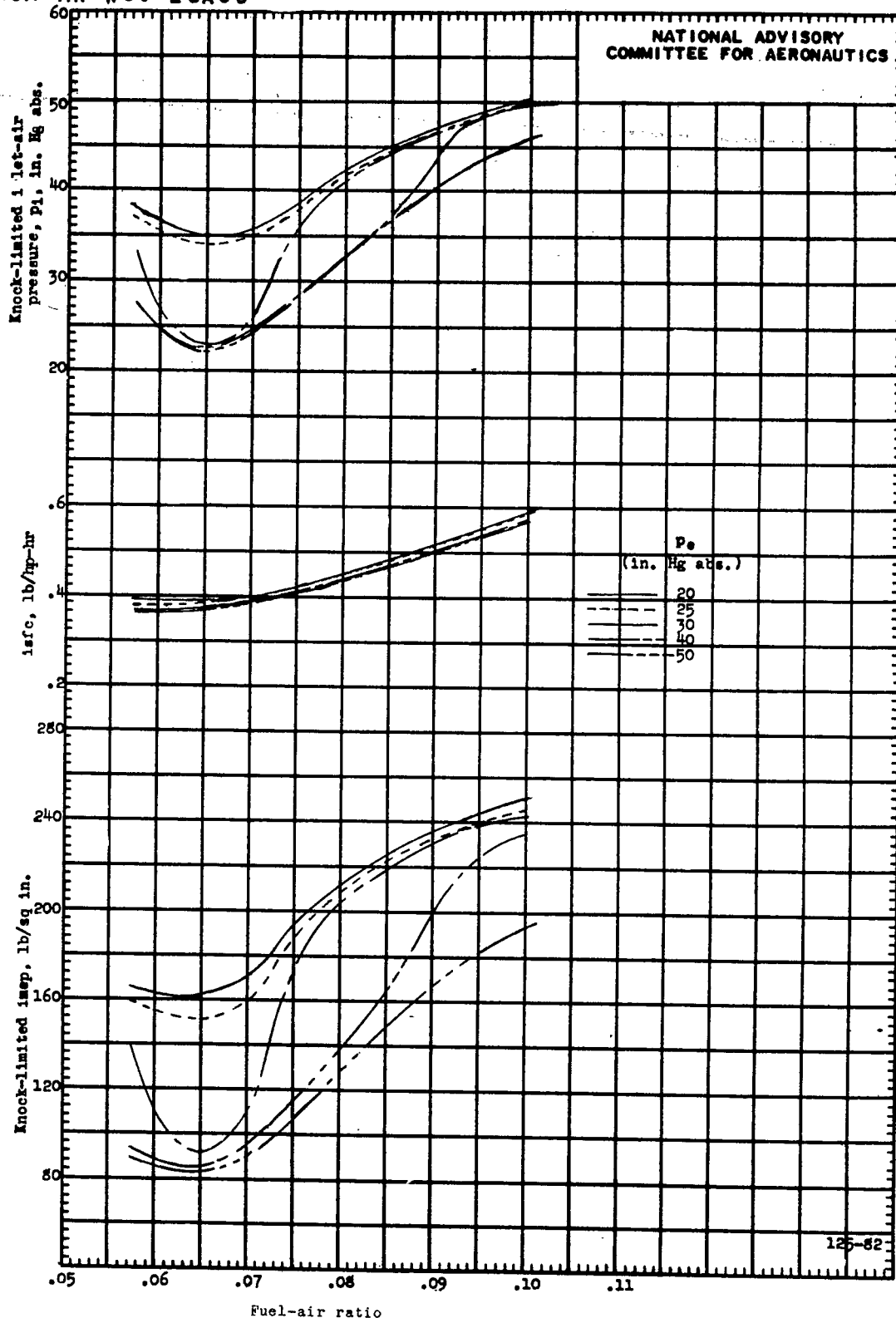


Figure 10. - Effect of exhaust pressure and of the critical $P_1 - P_e$ range on the knock-limited performance of the check-test cylinder A at constant exhaust pressures. (Cross plot from fig. 9.) Engine speed, 2100 rpm; inlet-air temperature, 250° F; spark advance, 20° B.T.C.; cylinder-head temperature, 450° F; compression ratio, 6.9; fuel, 28-R.

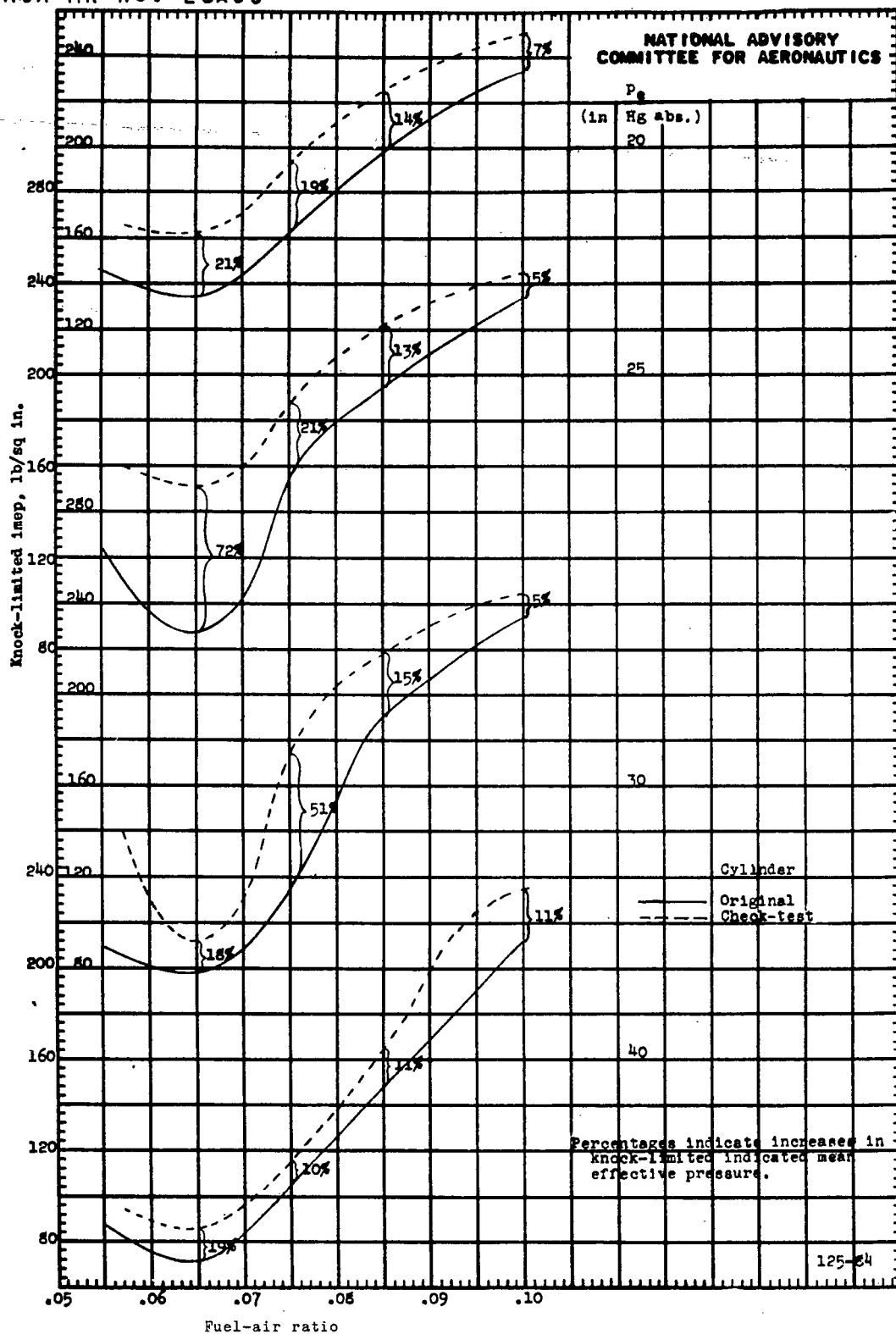


Figure 11. - Comparison of knock-limited performance of the original and the check-test cylinder A at several exhaust pressures. (Replot of figs. 5 and 10.) Engine speed, 2100 rpm; inlet-air temperature, 250° F; spark advance, 20° B.T.C.; cylinder-head temperature, 450° F; compression ratio, 6.9; fuel, 28-R.

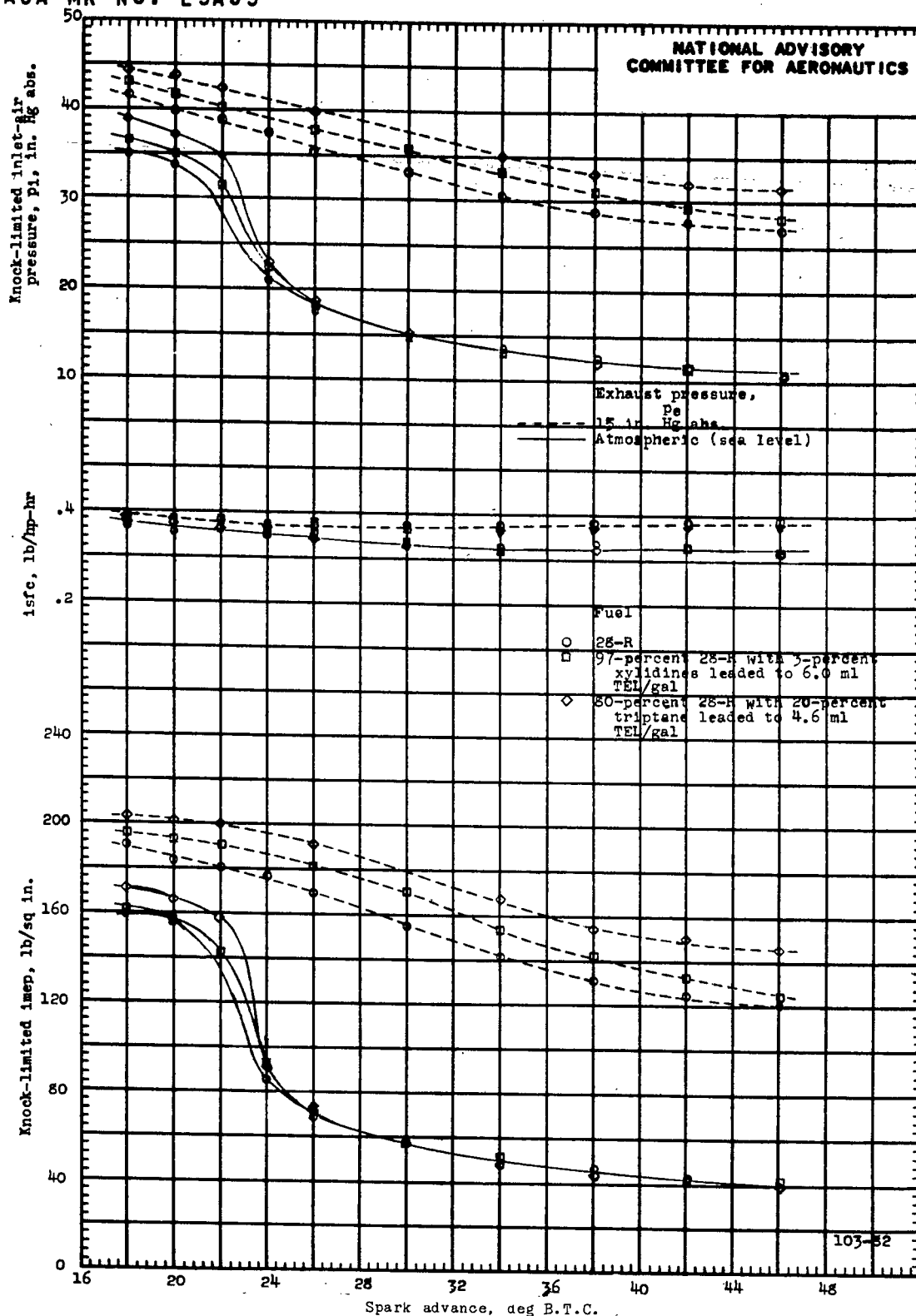


Figure 12. - Effect of exhaust pressure on knock-limited performance of three high-performance fuels in cylinder A in varied-spark-advance tests at a fuel-air ratio of 0.085. Engine speed, 2100 rpm; inlet-air temperature, 250° F; cylinder-head temperature, 450° F; compression ratio, 6.9.

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